Accelerometer-Assisted Tracking and Pointing for Deep Space Optical Communications: Concept, Analysis, and Implementations

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Abstract—NASA/JPL has been developing acquisition, tracking and pointing (ATP) technologies for deep space tracking and pointing of an optical communication beam using linear accelerometers to enhance pointing. Linear accelerometers provide excellent accuracy in sensing the vehicle's acceleration with the advantage of small size, low power, low cost, and a broad range of well developed products.

Accurate and stable pointing is the most critical function necessary to establish a successful free-space optical communication link. Generally known as the line of sight problem, it is also common to system requiring image stabilization, such as video cameras. The most dominant mis-pointing error source is spacecraft vibration that causes line-of-sight jitter during beam pointing. Line of sight stabilization using the detection and measurement of spacecraft vibration has been previously pursued with gyros, angle sensors, and more recently, angular rate sensors.

The goal of the ATP research is to achieve sub-microradian pointing for deep space optical communications. The most critical tracking parameter to achieve sub-microradian pointing under the spacecraft vibration is the tracking update rate. Since the degree of suppression of spacecraft vibration is proportional to the ability to measure it, faster measurements will improve the pointing. Current tracking systems rely on optical beacon sources such as ground based laser beacon, extended sources (such as Sun-illuminated Earth or Moon), and stars. However, for deep space ranges, the intensity of these beacon sources is not sufficient to support the required optical tracking rate that is often few kilohertz. However, the tracking rate can be increased by employing inertial sensors, which can propagate the line of sight between optical measurements, command the pointing mechanism, compensating for the spacecraft vibrations, effectively increasing the tracking rate.

In this paper, we will present the concept of accelerometer-assisted tracking, error analysis, and progresses made on its implementations.

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1. INTRODUCTION

Accurate determination of a ground receiver location and the pointing of a downlink communications laser beam are critical functions required for the success of any free-space optical communications. This function has been known, in general, as the line of sight (LOS) stabilization to both space-based camera and optical pointing systems. For the future deep space optical communications, the pointing requirements are very stringent and in the range of sub-microradians [1]. Because of the tight pointing requirements, major sources of mis-pointing need to be minimized. A key source of mis-pointing for deep space optical communications is the spacecraft (S/C) vibration caused by thrusters and other onboard instruments such as reaction wheels. Accurate pointing while subjected to S/C vibration requires fast commanding on a beam pointing mechanism (Fine Steering Mirror) which depends on fast tracking of the receiver location. One popular S/C vibration model based on the measured vibration spectrum of Olympus S/C indicates that vibration spectrum up to few hundred hertz needs to be measured to effectively reduce the pointing error to the sub-micro radian level. It has been reported that substantial reduction of pointing error can be achieved by using a focal plane array (FPA) capable of tracking at several kHz [2], [3], [4] when sufficient optical tracking signal is available.
A typical example of optical tracking is to locate a receiver position through the detection of laser beacon on FPA such as a CCD. The difference between the estimated position of the beacon and that of the transmit laser with a point-ahead angle becomes a pointing command to the fine steering mirror. Beacon sources other than the uplink laser include extended sources such as Earth and Moon, and stars. The

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common drawback of all these beacon sources, however, is that the light intensity is not usually sufficient to support the desired high tracking rate. Since the need for high tracking rate comes from the fact that the S/C vibration causes motion of the beacon on FPA, fast tracking using inertial sensors detecting S/C position relative to the measured uplink beacon position could augment the optical only tracking of beacon. Therefore, high frequency spacecraft vibrations can be measured by inertial sensors (inertial tracking) and low frequency spacecraft vibrations (such as those due to S/C deadbands) can be estimated by optical beacon sources (optical tracking). In the past, similar approaches have been attempted with the combination of gyro and angular displacement sensors (ADS) [10]. Other approach includes angular rate sensors instead of ADS [11].

In this paper, we present the feasibility for using a linear accelerometer for an ATP optical communications systems through a combination of analysis tied to experimental results. The advantages of accelerometers, which include small size, low mass, power, cost, broad range of well developed linear accelerometer technologies and the excellent performance demonstrated in recent flight missions [6] [7] made accelerometers the ideal starting point. The challenge is to therefore accurately estimate and correct the angular positions of S/C using the measurements of S/C vibrations.

2. Accelerometer Assisted Tracking

The architecture of the proposed tracking and pointing subsystem employs two tracking loops, one for low frequency measurements through optical tracking (in some sense, a correction update) and high frequency measurements through inertial tracking. This architecture is depicted in Figure 1. In order to use linear accelerometer pairs to measure angular displacements, either software or hardware implementation is required to perform double integration. Previously, both hardware and software implementation for double integration were attempted. However, hardware implementations (analog double integrator) were reported to have many significant problems whereas the proposed software implementation was limited to displacement signals with zero mean value due to the application of high pass filters [10], [11]. Our approach is to use the trapezoidal rule, a well-known numerical integration method, along with a least squares fit on a collection of accelerometer measurements and reference optical measurements. This allows the effects of acceleration bias, initial velocity error, and scale factor error to be minimized. The process of estimating single-axis angular displacement from linear accelerations is given in the following (two axes will require a minimum of three linear accelerometers).

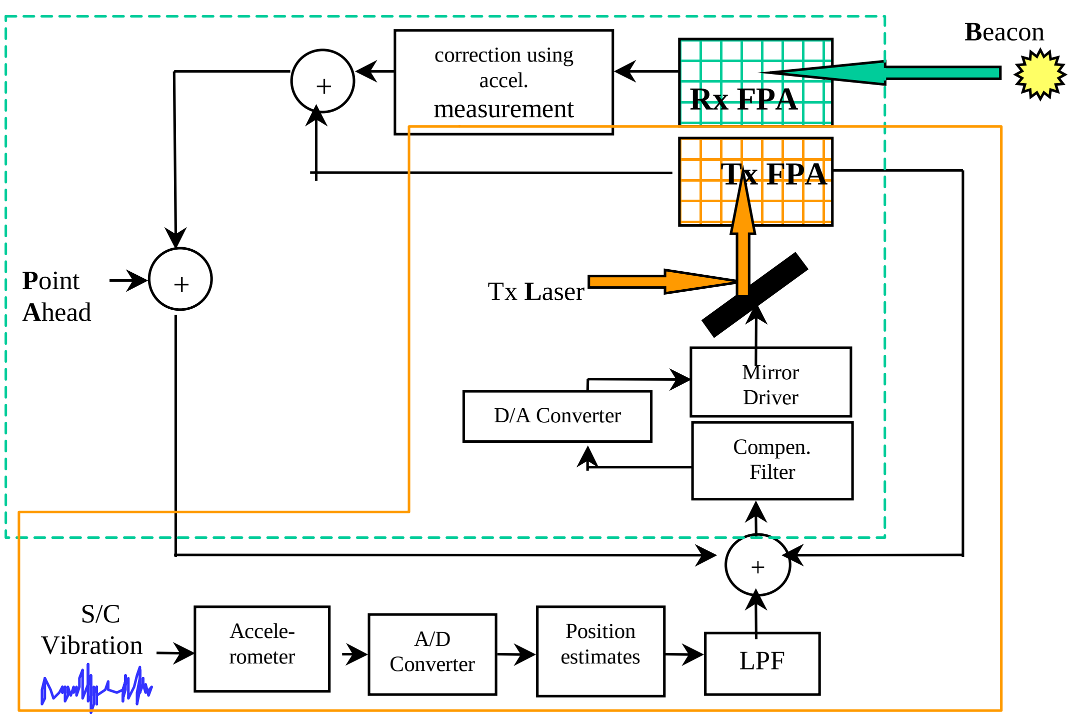

Figure 1. Accelerometer assisted tracking/pointing subsystem

A pair of parallel mounted accelerometers A_1 and A_2 are shown in Figure 2. The angle, θ, can be estimated from the individual readings of accelerometers, A_1 and A_2, after converting the accelerations into linear displacements, d_1 and d_2 with the small angle assumption.

$$\theta = (d_1 - d_2)/ l \qquad (1)$$

Since *l*, the separation, is a known measurable constant, θ is determined with the precision of A_1 and A_2. Angular displacements on two axis (α, β) can be obtained using three accelerometers as shown in Figure 3. Three accelerometers are placed on the y-z plane. Assume acceleration is in x-direction, then displacement estimation using accelerations from B and C gives an angular displacement (α) on x-y plane. Using A and the mean of B and C gives an angular displacement (β) on the x-z plane.

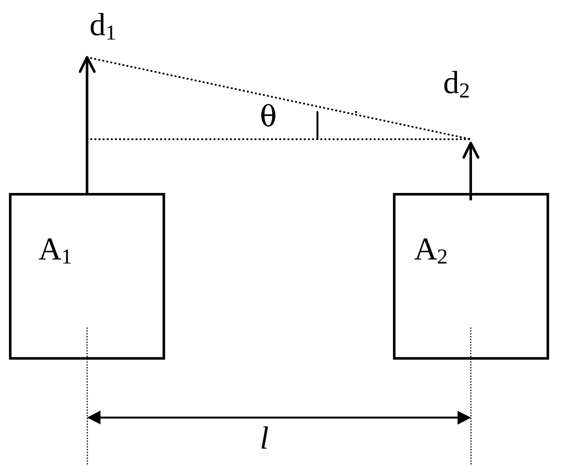

Figure 2. A pair of linear accelerometer arranged to estimate a single axis angular displacement

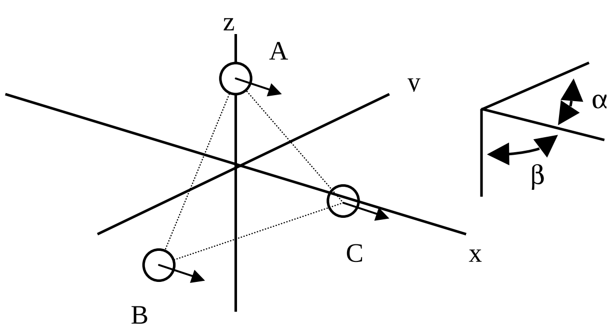

Figure 3. Triangular configuration of three accelerometers to estimate two axis angular displacements

3. REQUIREMENT ON ACCELEROMETER ACCURACY

There are two types of errors caused by the accelerometers that affect displacement estimation errors: accelerometer electronic noise and frequency response error. Electronic noise is the wide bandwidth random noise. Electronic noise is the primary error factor for displacement estimation while the frequency response error is the static error that is a function of frequency. The frequency response error is rather small and calibration can reduce it down to 0.5% for AlliedSignal QA3000 accelerometers. Therefore, we will focus on electronic noise for performance estimation hereafter. In order to estimate the displacement error from accelerometer noise, a displacement estimation equation in terms of acceleration needs to be derived. This has been reported in [12] and summarized in equation (1).

$$p_N = \sum_{i=2}^{N-1} (N - i) a_i \Delta t^2 + (N/2\text{-}2/3) a_1 \Delta t^2 + a_N \Delta t^2/6 + (N\text{-}1)\, v_1\, \Delta t + p_1 \qquad (2)$$

where

p_N: linear displacement at sampling time of N
a_N: acceleration measurement at sampling time of N
v_1: initial velocity
p_1: initial position
N: number of acceleration measurements

Notice that $N\Delta t$ is the integration time and $1/N\Delta t$ is the optical tracking rate. The corresponding position estimation error can be expressed as a function of the acceleration measurements noise (1 sigma value), σ_a, assuming the a_i's are iid (independent, identically distributed) random variables [12].

$$\sigma_{pN} = \Delta t^2\, \sigma_a \left(\sum_{i=2}^{N\text{-}1} (N\text{-}i)^2 + (N/2\text{-}2/3)^2 + 1/36 \right)^{1/2} \qquad (3)$$

An angular position estimation error can be derived from Eq.(1) assuming the two linear position estimates, d_1 and d_2 are iid random variables with its RMS error of σ_{pN} in Eq.(3).

$$\sigma_{\theta N}^{\ 2} = (\mathrm{Var}(d_1) + \mathrm{Var}(d_2))/l^2$$

$$= 2\, \sigma_{pN}^{\ 2} / l^2$$

$$\text{or} \qquad \sigma_{\theta N} = \mathrm{sqrt}(2)\, \sigma_{pN} / l \qquad (4)$$

The position estimation error (1 sigma value) using QA-3000 accelerometer noise of 76μg (10~500Hz) and sampling rates of 2kHz and 5kHz are plotted in Figure 4 for an integration period up to 100msec assuming accelerometer separation of 30cm. From this plot, requirements on accelerometer noise can be deduced. For sub-microradian pointing, angular displacement estimation error should not exceed 0.16µrad (0.071µrad*1µrad/0.45µrad) if we take previous mission studies such as Europa mission study where 0.071µrad was allocated to the displacement estimation error for the total RMS tracking error of 0.45µrad [1]. This translates to linear displacement error of 0.034µm that corresponds to the maximum integration period of 0.03second or optical tracking rate of 33Hz for 5kHz sampling. Since the angular displacement error is directly proportional to the accelerometer noise (equation 3 and 4), different optical tracking rate will result in variations from 76µg. Table 1 shows the requirements on accelerometer noise when various optical tracking rates are used assuming 5kHz accelerometer sampling.

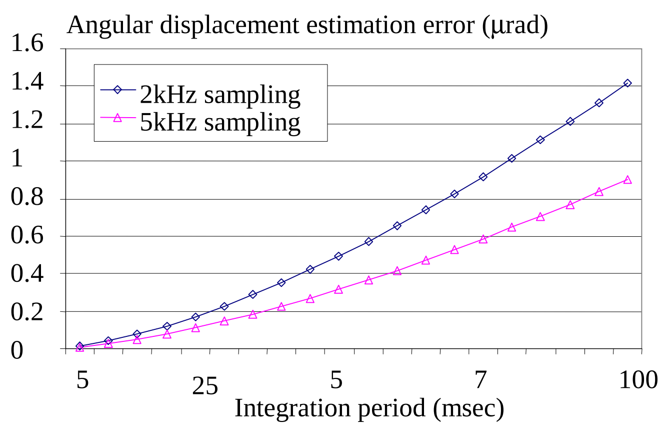

Figure 4. Angular displacement estimation error vs. integration period assuming 0.3m separation of two accelerometers. Acceleration measurement error of 76µg was used for two sampling frequencies (2kHz and 5kHz). Notice that higher sampling frequency gives better performance.

rate	10Hz	20Hz	30Hz	50Hz	100Hz
noise	13µg	38µg	69µg	152µg	428µg

Table 1. Requirements on accelerometer noise for various optical tracking rates for pointing error of 0.16µrad due to accelerometer.

4. Experiments - concept validation

In this section, our objective is to validate the concept of the accelerometer assisted tracking using experimental results. To achieve this goal, we took the following steps:

(a) validation of displacement estimation algorithm
(b) validation of optimization algorithm for initial velocity error
(c) integration of (a) and (b) with the tracking/pointing subsystem
(d) setup of accelerometer and laser beacon on shake table
(e) operation of accelerometer assisted tracking with various optical tracking rates

Figure 5 shows the setup to demonstrate the accelerometer-assisted tracking concept. The 12bit ADC is recognized to be a limitation of our system, but is sufficient to functionally demonstrate the concept.

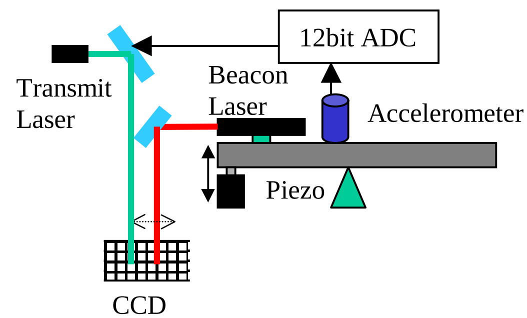

Figure 5. Setup for accelerometer-assisted tracking concept demonstration.

Step (e) of the above validation procedures is worth explaining in detail for the concept demonstration. Laser beacon from the shake table was sampled at 1kHz on the CCD and the accelerometer on the shake table was also sampled at 1kHz. The vibration frequencies were set to 35Hz and 45 Hz with displacement ranges up to few pixel distances (1 pixel =45µrad). In order to establish a reference, optical only tracking was maintained at 1kHz while the beacon centroids and transmit laser centroids were logged to estimate the tracking performance later. Next, accelerometers were used in tracking and the optical tracking rate was reduced to 500Hz while maintaining the sampling rate of accelerometer constant at 1kHz. The other optical tracking rates were 333Hz, 250Hz, and 200Hz. Figures 6 and 7 show the tracking of the sinusoidal motion of the beacon at 45Hz with optical tracking only and with accelerometer assisted tracking. Table 2 shows RMS tracking errors at various optical tracking rates for the two vibration signals.

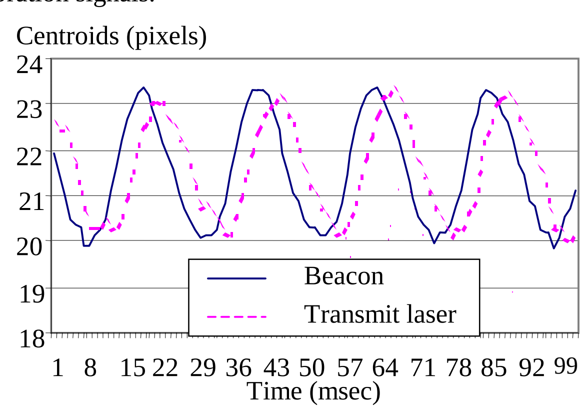

Figure 6. Optical tracking at 1kHz with vibration signal of 45Hz.

Centroids (pixels)

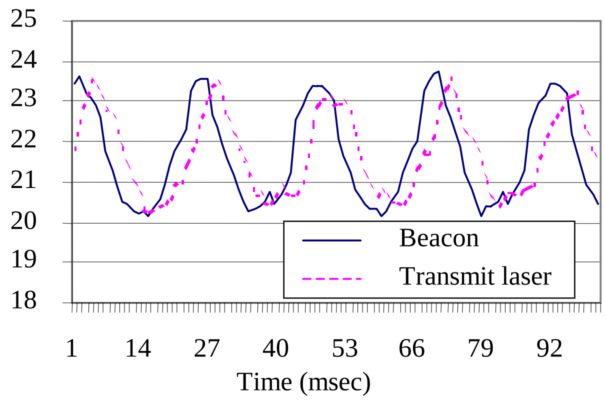

Figure 7. Accelerometer assisted tracking with optical tracking of 200Hz and vibration signal of 45Hz

Vibration of 35Hz

rate	1kHz	500Hz	333Hz	250Hz	200Hz
error	0.77	0.77	0.84	0.90	1.04

Vibration of 45Hz

rate	1kHz	500Hz	333Hz	250Hz	200Hz
error	0.93	0.93	0.95	0.97	0.97

Table 2. Measured RMS tracking errors in pixels for the accelerometer assisted tracking with various optical tracking rates

Figure 6 and 7 clearly show that tracking performance using accelerometer is comparable to that of optical tracking only. This is confirmed in Table 2 where the degradation due to accelerometer is almost negligible for 45Hz vibration. The performance degradation is a function of the vibration signal frequency as is evidenced for 35HZ vibration signal in Table 2 which shows about 25% of gradual increase in error from optical tracking rate of 1kHz to 200Hz. Nevertheless, the results from Figure 6, 7 and Table 2 demonstrates the concept of the accelerometer-assisted tracking. The gradual performance degradation was expected due to the displacement estimation error that is a function of random noise coming from accelerometer, accelerometer sampling rate, building vibration, A/D converter quantization, and other electronic noise. Currently, the total RMS random noise using 12bit A/D converter is between 4 to 8mV compared with 76μg from QA-3000 accelerometer only. We are working on the upgrades of the hardware to minimize the total random noise level to less than 100 μg., by increasing both the accelerometer sampling rate and the resolution of the ADC. We believe that this can be achieved as the measured minimum vibration level was reported as 80μg.[6] Once the noise level is reduced, the performance degradation will be small and more predictable as we reduce the optical tracking rates.

5. Conclusion

We presented the concept, error analysis, and demonstration of accelerometer-assisted tracking. This inertial sensor (accelerometer) tracking approach promises the improvements of the performance of ATP subsystem while using the low intensity beacon sources such as uplink laser, stars, and Sun-illuminated Earth images as optical references. The primary challenge in using accelerometers to achieve the desired tracking performance is the minimization of the total random noise in acceleration measurements. Future work includes upgrades of hardware to lower the random noise. For flight implementations, there are other error sources that probably need to be estimated. One of the examples includes accelerometer-to-accelerometer distance that will likely vary with temperature and disturbances.

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